TO DETERMINE THE DYNAMIC TOUGHNESS PROPERTIES OF CAST STEELS

FINAL REPORT

BY

ALLOY CASTING INDUSTRIES LIMITED

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SUMMARY

A program on the fracture toughness testing of commercially produced LCC and LC4 cast steels was performed. The program consisted of the evaluation of Charpy (CVN), K_{IC} & K_{ID} properties of test materials derived from different size castings (2" and 5") at cryogenic temperature.

The test results suggested that even at cryogenic temperature, a large compact tension sample (larger than 1-1/2" in width) is required to meet the ASTM E399 requirements of a valid K_{IC} test. Compared to the K_{ID} test results, the Charpy (CVN) results always indicated higher ductile/brittle transition temperatures for the above test materials. In addition, the size of the castings (2" or 5") did not have any significant effect on the ductile/brittle transition temperatures.

SOMMAIRE

Un programme d'essai a fait au sujet de la résistance de fracteur des pièce d'acier fondu en deux alliage (ASTM 352 - LCC et LC4). Le programme a consisté de l'evaluation des caractéristiques qui sont indiqué par les facteurs Charpy Vee Notch, K_{IC} et K_{ID} aux temperatures cryogeniques.

Les resultats ont suggesté que, même les temperatures cryogeniques, une grande barre d'essai (plus que 1 1/2" d'épaisseur) est nécessaire à satisfaire les conditions d' ASTM E399, pour un essai valide de K_{IC}. Les valeurs Charpy sont toujour indiqué une temperature de transition ductile/fragile plus haut que l'essai de K_{ID}. De plus, l'éppaisseur des pièces n'a pas eu un effet significatif aux temperature de transition ductile/fragile.

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1. INTRODUCTION

For many applications, castings have a decided advantage over wrought materials, since complex shapes can be produced economically. Cast steels have the potential to be both stronger and more ductile than many competitive materials. Thus, there is increasing demand in Canada for cast steels in pipelines, offshore platforms and water turbine application.

In selecting alloys for a specific product mechanical properties such as yield strength, tensile strength, ductility and impact (CVN) energy are routinely utilized in design considerations; however, other specialized design parameters are being used in certain circumstances. For example, in recent years, a considerable amount of information on the toughness properties, such as the plane strain fracture toughness, K_{IC}, of wrought alloys, has been accumulated because of the need to ensure the integrity of critical components in structures such as air-craft, pipelines and ships. However, for cast metals,

there is a general lack of information on their fracture toughness properties, thus restricting their use for applications in which fracture resistance is important.

With increasing exploration activities in northern regions and in offshore areas, where adverse environmental conditions are encountered, the establishment of low temperature fracture toughness properties of cast steels has become a necessity.

Fracture toughness is a property of a material to resist the growth of an existing flaw or crack. Determination of this property is, therefore, imperative to the selection of material for specific components which are subjected to critical stress conditions. When dealing with high-strength materials, thick sections or in the case of some ferrous alloys, low temperatures, brittle fracture is a possibility. Under these circumstances, the fracture toughness of the material is defined by the plane-strain fracture toughness parameter, K_{IC} (ref. ASTM E399). The same parameter cannot readily be obtained for ductile materials because the section thickness required to

perform a valid K_{IC} determination is impractically large. To overcome this limitation, several approaches to determining the fracture toughness of ductile materials (such as low strength cast steels) have been proposed; for example, the J-integral and COD tests. All these "quasistatic" fracture toughness test methods have extended the linear elastic fracture mechanics (LEFM) range to incorporate the plasticity of ductile materials prior to fracture.

One of the complicating aspects in defining the fracture toughness of metals is that the fracture mode is highly dependent upon local mechanical conditions, expecially conditions related to crack tip constraint and strain rate. Fracture can occur at stress levels below or above the yield stress depending upon flaw size, section thickness and strain rate. Furthermore, the fracture performance of most of the conventional steels is highly dependent upon temperature, which results in a transition from ductile to brittle fracture over a relatively narrow temperature range. For these materials, low temperatures and thick sections promote fracture by a cleavage (brittle) mode. On the other hand, high temperature

fracture can occur in a ductile mode even for the case of maximum mechanical constraint associated with very thick sections.

The effect of strain rate on fracture toughness is recognized by the introduction of "dynamic fracture toughness" factors such as K_{ID}. These can be determined by performing the standard K_{ID} tests at higher-than-specified strain rates. Although no standard conditions have yet been specified for determining K_{ID}, this test is useful for outlining the lower boundry of fracture toughness in much the same way as the deleterious effects of low temperatures can be estimated by performing low strain rate tests at low temperatures. Nevertheless, these tests are difficult to perform and interpret, and there has been little progress in applying them to castings.

Current data on the toughness of materials under high strain rate (impact) conditions, are provided, to some extent, by the Charpy "V" notch (CVN) impact test. However, the energy absorption values determined by this method are relative and can only be related empirically to

structural performance. Furthermore, CVN energy values cannot be related to the size of the defects present in the material, since the measured energy is associated both with initating and propagating a crack. Nonetheless, this technique has the advantage of simplicity, low cost, and wide acceptance.

In this work, commercially produced LCC and LC4 cast steels were evaluated (See appendix A). The test program on fracture toughness evaluation consisted of metallographic examination, impact energy (CVN), K_{IC} and K_{ID} testings.

2. EXPERIMENTAL CONDITIONS

2.1 Materials

Cast steels of ASTM A352 Grade Type LCC, and LC4 materials were selected for this test program.

For a given composition of cast steel, two different types of heat treatments, quench and temper and normalize and temper were employed for LC4 and LCC materials respectively. Sample castings in two section sizes (e.g. 2" and 5") were made to study the effect of cast section thickness. The total number of material

conditions to be evaluated amounted to four, comprising two heat treated materials of two section thicknesses.

3. Test Materials

3.1 Sample Castings

The test samples were extracted from the centre section of cast steel billets of two sizes.

BILLET A 2" x 4-1/2" x 17" Long

BILLET B 5" X 8-1/4" X 17" Long

The billets were cast in the horizontal position using chemically bonded sand moulds (phenolic-urethane binder system). The metal was introduced to the mold cavity through 4 ingates distributed, along the length. Each billet had one centrally located riser directly off the cope side of the billet.

Two compositions were chosen as representative of the low temperature grouping as defined in ASTM standard specification A352.

The cast billets were heat treated following fettling and shot blast cleaning as follows:

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The following billets require heat treatment as described:

BILLET NO'S	NORMALIZE TEMP / TIME	QUENCH MEDIA	TEMPER TEMP / TIME
LCC 8" X 5" Blocks HEAT 7054 Blocks 1,2,3,4,5	1650 °F 5 hrs	Air	1100 °F – 5 hrs
LC4 8" X 5" Blocks HEAT 7070 Blocks 1,2,3,4,5	1800 °F 5 hrs	Water	1100 °F – 5 hrs
LCC 4" X 2" Blocks HEAT 7031 Blocks 1 - 7	1650 °F 2 hrs	Air	1100 °F – 2 hrs
LC4 4" X 2" Blocks HEAT 7072 Blocks 1,3,8,9,10	1800 °F 2 hrs	Water	1100 °F – 2 hrs

***All blocks to be air cooled following Temper.

NOTE: Approximate weights: 8" X 5" Block - 200#
4" X 2" Block - 40#

FIG. NO. 1

Each cast billet was x-rayed along it's entire length for comparitive checking of its quality. Each test bar was stamped with an identification number which catalogued it's billet of origin, and it's position within the billet. The bars were cut from the billets using "band saw" equipment and machined to final dimensions using conventional metal cutting machine tools. (See Fig. No.2.)

The test bars were chosen with a view to conforming with the requirements of the respective test materials as follows:

ASTM (E23) ** for CVN Tests

ASTM (E399) * FOR K_{IC} AND K_{ID} TESTS

(*Appendix A, ** Appendix B)

See Fig. No. 3 and 4

EXTRACTION OF TEST BARS FROM CAST BILLETS

*"Heart" of billet used for test bars as shown

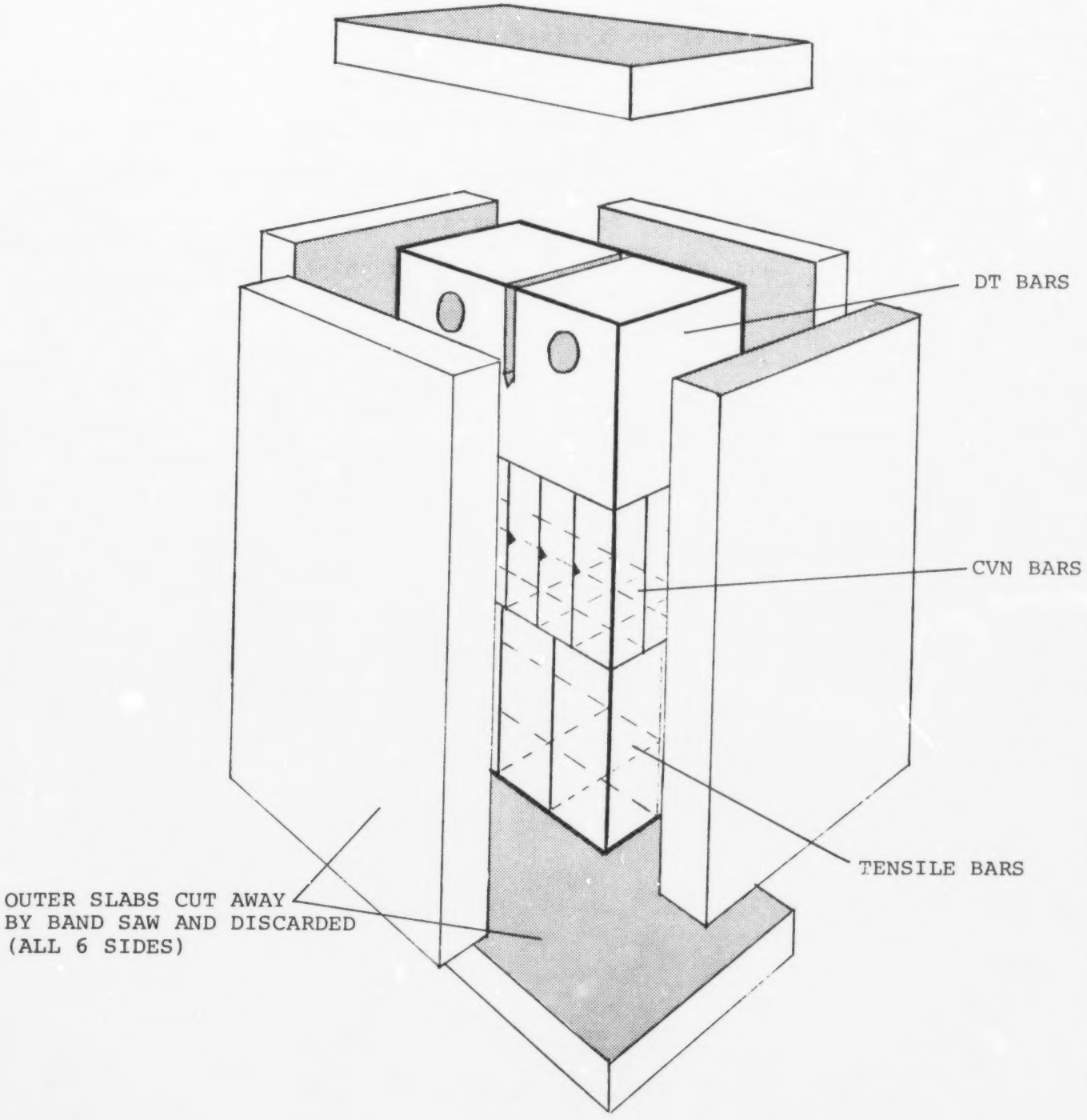


FIG NO. 2

SPECIMEN SIZE, CONFIGURATION AND PREPARATION

Fig. No. 3 shows a standard compact tension specimen. Compact tension test specimens were employed in performing all of the K_{IC} and K_{ID} tests. A precracking notch was introduced to each compact tension samples as recommended in ASTM E299.— A2.4. To assure that a straight crack front was achieved in each sample during mechanical pre-cracking, an ultrasonic probing system was used to monitor the crack front profile.

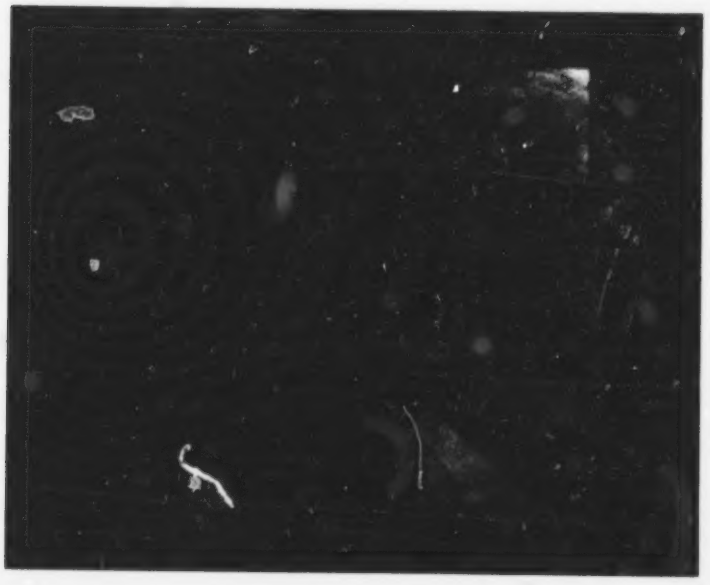
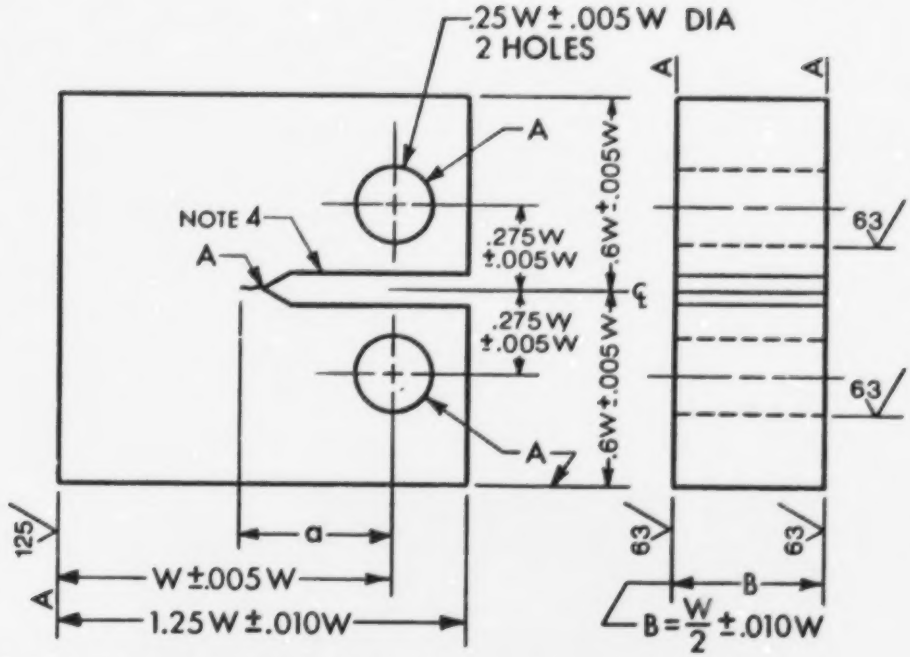


FIG. No. 3



NOTE 1—*A* surfaces shall be perpendicular and parallel as applicable to within 0.002 *W* TIR.
NOTE 2—The intersection of the crack starter notch tips with the two specimen surfaces shall be equally distant from the top and bottom edges of the specimen within 0.005 *W*.
NOTE 3—Integral or attachable knife edges for clip gage attachment to the crack mouth may be used (see Fig. 2 and 3).
NOTE 4—For starter notch and fatigue crack configuration see Fig. 4.

Compact Specimen C (T) Standard Proportions and Tolerances

FIG. 4 Compact Specimen C (T) Standard Proportions and Tolerances

NOTE: For the purposes of this study w=3". For more consistent results dimensional tolerance have been reduced to + 003" (I.001W)

4.0 Testing Criteria

In the initial proposal for this study, it was anticipated that K_{IC} data could be obtained through a J-integral approach.

The objective of the J_{IC} procedure is to determine the value of J at the initiation of crack growth. This method involves pin loading of fatigue precracked specimens, and determining J as a function of the crack growth. Therefore, the value of the physical crack growth, "Δap", is an important parameter in the determination of J_{IC}.

The technique of measuring "Δap" as recommended by ASTM are as follows:

1. Heat tinting method in which the sample is heat tinted at 300 degrees C for 10 minutes for each unloading cycle at selected displacement levels, to mark the crack extension that occurred during loading.

2. An unloading compliance method - in which the crack growth is determined entirely from the unloading compliance. (See ASTM E813 Annex A1.) It has been mentioned in ASTM recommended standard E813 that this

technique is quite prone to error and must in any case be verified by the heat-tint method.

In view of the above options available in measuring "Δap". The first technique was initially employed. However, due to the fact that most of the experiments were performed at low temperatures, heat tinting to mark "Δap" required heating the samples from say - 100 degrees C to 300 degrees C, then cooling down to -100 degrees C again for further testing, and at least four cycles of heating and cooling were needed to establish a J-integral value. This technique was found to be unfeasible due to the fact that the moisture accumulated in front of the precracked tip at low temperature was extremely difficult to remove. As a result, heat tinting operation was not successfully performed, and this technique of measure "Δap" for this particular experiment was considered cumbersome and unsuitable.

The second technique of measuring "Δap" was also attempted. As mentioned in ASTM E813, this technique is very much prone to error. In addition, with the high rate of loading in the case of dynamic fracture testing, unloading at an interval of 0.01 sec. to obtain the compliance is just not achievable.

Since both of the ASTM recommended techniques were found unsuitable, two other techniques to monitor the "Δap" were attempted. The first technique involved the use of ultrasonic method of monitoring the crack front. This had provided extremely satisfactory result in monitoring the crack advancement in our calibration trials. Nonetheless, this technique also required holding of the load while monitoring the crack front, and thus becomes unfeasible in the dynamic testing experiments.

Another technique being considered was the D.C. potential drop technique. Although this would serve to monitor the crack front continuously without having to cause any interruption in the loading rate, there are areas of concern in using this technique for this work. Firstly, the electrical resistivity is a function of temperature, which means that the calibration between the electrical signal and crack front profile has to be established for each material and at each test temperature. Secondly, due to the large test temperature range, the crack front profiles of each material are going to behave quite differently, at different test temperatures, due to the change in the ductility of the material at those different temperatures. Consequently, this temperature effect on "Δap" has to be determined. This technique of

monitoring "Δap" though feasible, required extensive work and large quantities of test samples in order to calibrate the test procedures, and is therefore beyond the scope of this testing programme.

In view of the results of the initial experimental trails, and considering the objective of this program (to investigate the validity and the correlation of the fracture toughness properties of the materials as determined by static and dynamic test techniques) the K_{IC} and K_{ID} test methods were considered relatively suitable. Though it had been considered, prior to K_{IC} testing, that the sample geometry might not provide valid K_{IC} test data, nonetheless, the following rationale serve to justify the employment of these techniques.

1. The nature of this program required fracture toughness testing to be performed at low temperatures, as well as with both quasi-static and dynamic loading rate. From the preliminary experimental tests conducted (as mentioned earlier), it has been found that it is not feasible to conduct J-integral testings under the programs test conditions and within the program budget.

2. Part of the objective of this program is to determine and correlate fracture toughness of the materials as determined by static and dynamic test techniques. K_{IC} and K_{ID} test techniques are suitable in providing fracture toughness data in both static and dynamic cases, even at the low temperature regime.

3. In the preliminary tests, though it was indicated that the room temperature K_{IC} value did not meet with the plane strain fracture requirements, it was considered that both the low test temperatures as well as the fast loading rate would promote plane strain fracture condition, which would serve to differentiate the fracture toughness results derived from different test conditions.

4. According to ASTM Standard E399-83, it is mentioned that in the event the sample size is not big enough to provide a valid K_{IC}, "The specimen strength ratio determined by this method will often have useful significance. However, this ratio, unlike K_{IC}, is not a concept of linear elastic fracture mechanics, but can be a useful comparative measure of the toughness of materials when the specimens are of the same form and

size, and that size is insufficient to provide a valid K_{IC} determination, but sufficient that the maximum load results from pronounced crack propogation rather than plastic instability".

In view of the foregoing, in this test program, it is the K_C values of LCC and LC4 materials under plane strain conditions which are being evaluated.

4. Testing Criteria

4. 1. The Physical Basis of Fracture Toughness and Stress Intensity Factor:

The importance of energy in fracture was demonstrated by GRIFFITH (2) for hard brittle materials (such as glass). He showed that the necessary energy required to propogate cracks could be derived from the release of elastic strain energy as that crack propogates. Instability occurs when the crack is long enough or the stress high enough so that the energy released in a increment of crack extension just balances the surface energy required to produce the extra area of fracture surface.

The energy equasion is expressed as

$$\sigma = \sqrt{\frac{E2\gamma}{\pi a}}$$

where σ, a and γ are the fracture stress, crack length and surface energy respectively.

This equasion shows how fracture stress (σ) decreases with increasing crack length (a). With metals which tend to be plastic by nature, the surface energy factor 2 is replaced by the factor Gc - the "energy absorbed in plastic deformation per unit of crack extension". A term more commonly known as the "critical strain energy release rate".

The equation is thus:

$$\sigma = \sqrt{\frac{EGc}{\pi a}}$$

Materials such as glass are embrittled even by fine scratches. Metals, where Gc is typically about $10^3 \gamma$, are embrittled by macroscopic cracks only. Unfortunately, as stronger alloys are developed, the gain in increased resistance to deformation becomes a loss, at the point where it matters, for toughness - at the leading edge of a crack. Plastic deformation, becomes more localized, and hence Gc becomes smaller.

So, in general, the price we pay for increased strength is a decrease in both toughness and the limiting flaw size which we can tolerate.

Fracture mechanics relies upon this basic formula, however usually expresses it in terms of the parameter K_C - the "fracture toughness" where $Kc^2 = EGc$.

The formula thus becomes:

$$\sigma = \frac{Kc}{\sqrt{\pi a}} \qquad (1)$$

The Griffith theory of fracture presented above is obtained via an analysis of the energy of fracture based on linear-elastic theory. Derived from this, Linear-Elastic Fracture Mechanics (LEFM) utilizes the critical stress intensity factor, K_C, as a fracture criterion for situations where crack propagation is accompanied by little or no plastic deformation. Quantitatively, this means that the extent of crack tip plasticity (the range over which the yield stress is exceeded at the crack tip) should be not greater than one fiftyeth (1/50) of the dimension of the structure including the crack length. Since this is the case in many practical situations, LEFM has wide applicability.

LEFM provides an analytical procedure that relates the (elastic) stress field in the vicinity of a crack tip to

other parameters, such as the applied stress, the size, shape and orientation of the crack. Thus, it permits representation of the material fracture properties and the stress field at the crack tip in terms of a single parameter, the stress intensity factor, K. This is true for all crack lengths up to the critical crack length, at which point $K=K_C$ and fracture occurs. To understand the origin and significance of K, we must examine the elastic stress field which exists within the vicinity of a crack tip, when a load is applied.

A small segment of the crack front can be regarded as a straight line surrounded by a local two-dimensional stress-strain field (a field which does not change with position along the segment, as illustrated in Fig. 5, for the opening mode.)

The stress fields surrounding a crack tip can be divided into three basic types, each associated with a local mode of deformation: (1) the opening mode is associated with local displacements in which the crack surfaces move directly apart, (2) the forward sliding mode is characterized by displacements in which the crack surfaces slide over one another normal to the crack

front, and (3) the parallel shear-mode finds the crack surfaces sliding with respect to one another parallel to the crack front. In pacticular, if we assume Cartesian coordinates as shown in Figure 5, then on the plane y = 0.

For Mode 1

$$\sigma_x \neq 0, \quad \sigma_y \neq 0, \quad \sigma_z \neq 0, \text{ and } \tau_{xy} = 0 \qquad (2)$$

For Mode 2

$$\tau_{xy} \neq 0 \text{ and } \sigma_y = 0 \qquad (3)$$

For Mode 3

$$\tau_{yz} \neq 0 \text{ and } \sigma_y = 0, \text{ and } \tau_{xy} = 0 \qquad (4)$$

ASTM E616 gives additional details.

In any problem, the superposition of these three modes is sufficient to describe the most general case of crack-tip deformation and stress field. Moreover, the stress field at the crack tip can be treated as one or a combination of these three basic types of stress fields. It is convenient to add Arabic numerals 1,2, and 3 as subscripts to various symbols to indicate the mode. Use

of Roman numerals I, II and III designates the same modes specialized to a condition of plane strain at the crack front, viz: K_I, K_{II}, and K_{III}. Mode I is the more common occurance in engineering structures and laboratory testing.

The stress intensity factor K is the magnitude of the crack tip stress field for a particular mode in a homogeneous linear-elastic material.

In addition to the Cartesian coordinates used above, assume cylindrical coordinates, r, θ, and z, which are also shown in Figure 5. From linear-elastic stress analysis, assuming an isotropic solid, the stresses very close to the tip for a Mode stress field are given by

$$\sigma_x = \frac{K}{\sqrt{2\pi r}} \cos\frac{\theta}{2}\left(1 + \sin\frac{\theta}{2}\sin\frac{3\theta}{2}\right) \quad (5)$$

$$\sigma_y = \frac{K}{\sqrt{2\pi r}} \cos\frac{\theta}{2}\left(1 - \sin\frac{\theta}{2}\sin\frac{3\theta}{2}\right) \quad (6)$$

$$\tau_{xy} = \frac{K}{\sqrt{2\pi r}} \cos\frac{\theta}{2}\sin\frac{\theta}{2}\cos\frac{3\theta}{2} \quad (7)$$

K is constant used in the general form of the stress function and is constant for a given crack and applied

stress. By comparing the general form of the stress function to particular cases, equations for K can be obtained. These equations are of the form:

$$K = C_1 \sigma \sqrt{\pi a} \qquad (8)$$

where C_1 is a geometry factor (between 1 and 1.5) and is known for most configurations encountered in practice, σ is the applied stress at infinity and "a" is equal to 1/2 crack length.

K is a function of applied stress and crack length and is independent of material, i.e., analogous to a stress. A related parameter is G, which is termed the crack extension force as it represents the loss of stress field energy at the crack tip per unit of new fracture area during an increment of forward crack extension. G is simply related to K as $K^2/E = G$.

Fracture mechanics is based on the philosophy that at a critical crack tip stress field, unstable crack extension will occur. Thus for a material in a given metallurgical condition, there is a critical value of K, called K_c (equivalently, $G = G_c$). This is a material

property analogous to UTS: K_C is defined as the fracture toughness of the material. In this test program, it is the K_C values of LCC and LC4 material under mode 1 condition (i.e. K_{IC}), that are being evaluated.

(1) A.A. Griffith, Phil. Trans. Roy. Soc., 221 (1920) 163.

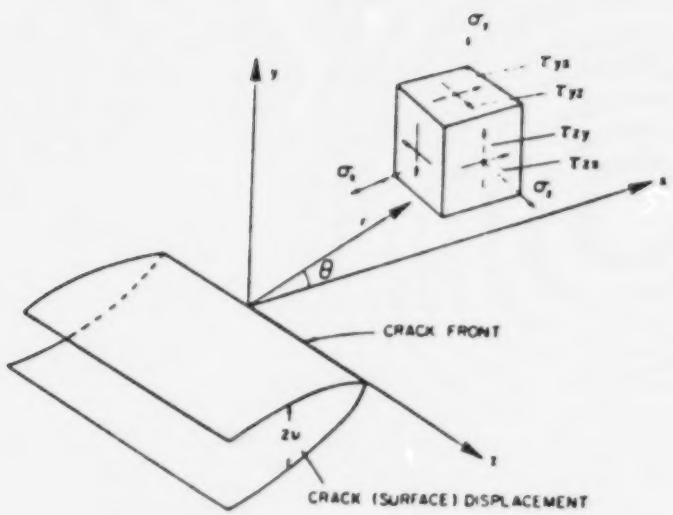


FIGURE 5. Coordinates for analysis model of a crack showing x,y,z, and r, 0 at the crack front. The crack (surface displacements illustrated here are for Mode 1 (opening mode).

4.2 Temperature

The tests were conducted at five different temperatures, ranging from cryogenic to room temperatures, in order to estimate the ductile-brittle transition temperature indicated by CVN energies. Five temperatures (near the ductile-brittle transition temperature as determined by the CVN tests) were employed for K_{IC}, and K_{ID} testing to provide a basis for comparison with other data.

4.3 Loading Rates

A dynamic loading rate conforming to the ASTM Standard E399 was employed to establish the K_{IC}, and K_{ID} testing conditions. The only different experimental condition in performing the K_{IC} and K_{ID} test, is the loading rate. In the previous section, a method of measuring stress intensity factor was already described. According to ASTM recommended test method of K_{IC}, for compact tension specimen, the rate of increase of stress intensity is within the range from 30 to 150 Ksi$\cdot\sqrt{in}$/min. In the case of K_{ID} testing, for compact tension specimen, the rate of increase of stress intensity is in excess of 150 Ksi$\cdot\sqrt{in}$/min.

In this work, rates of increase of stress intensity factors for K_{IC} and K_{ID} testing employed in this work are as follows:

For K_{IC} test - 1.2×10^{2} Ksi in/min

For K_{ID} test - 1.2×10^{4} Ksi in/min

4.4 Load, Energy and Displacement

The load, energy and displacement measurements were carried out in conformity with the ASTM E 23 and E399 standards.

4.5 Quasi-Static Fracture Toughness K_{IC}

4.51 Specimen Preparation

Compact tension specimens complying with the ASTM E399 standard were used in the plane strain fracture toughness evaluation. A sample size of 3.6" X 1.5" X 3.75" was utilized both for K_{IC} and K_{ID} testing.

4.52 Testing

The test procedure complied with ASTM E399-81, as given in Appendix A.

4.53 K_{IC}

The K_{IC} values were calculated from the load by equations that have been established on the basis of elastic stress analysis of specimens of the type described in ASTM E399.

4.6 Dynamic Fracture Toughness Testing

4.61 Impact Test (CVN)

4.62 Specimen Preparation

Notched longitudinal test specimens complying with the ASTM A370 standard were used.

4.63 Testing

Test procedures complied with ASTM Standard ASTM E23, as given in Appendix B. Four test temperatures other than ambient temperature were employed in order to establish the ductile-brittle transition temperature. Three specimens per temperature were tested.

4.64 K_{ID}

Specimen preparation and testing procedures used in establishing K_{ID} were identical to those used in

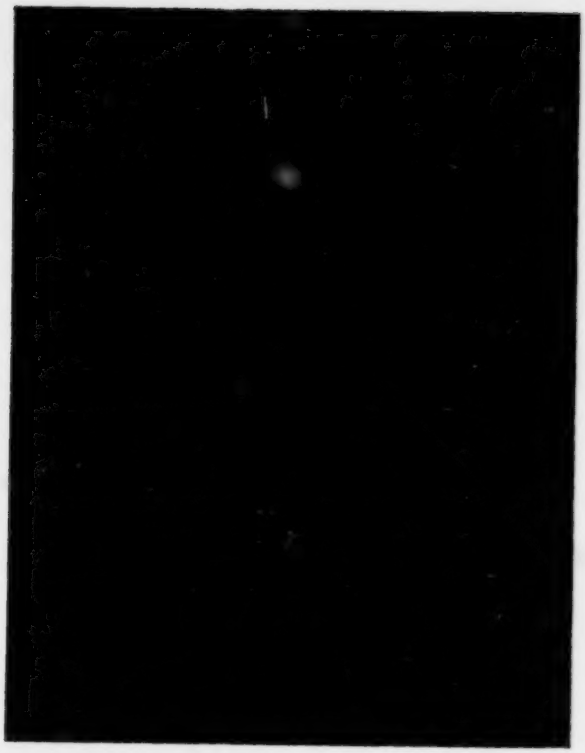


FIGURE 6

Microstructure of LCC material - (from 2" Casting)
Mag.X100.

FIGURE 7

Microstructure of LCC material (from 5" Casting)

Mag.X100.

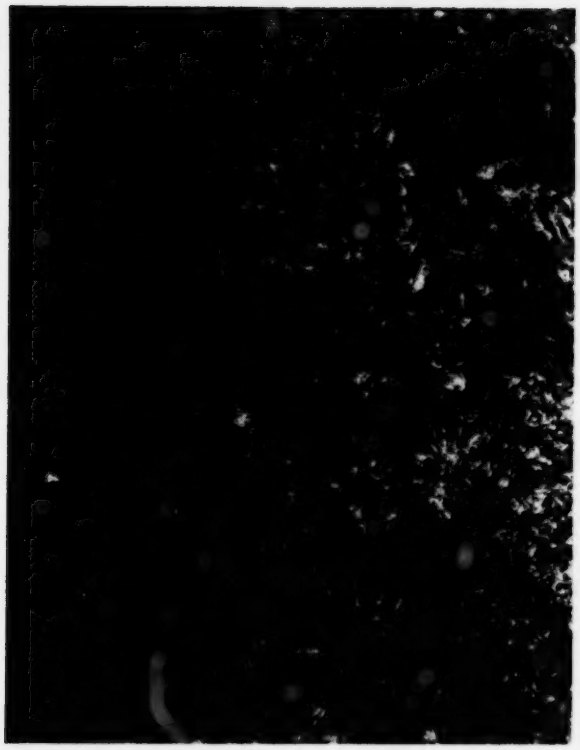


FIGURE 8

Microstructure of LC4 material - (from 2" Casting)

Mag.X100.

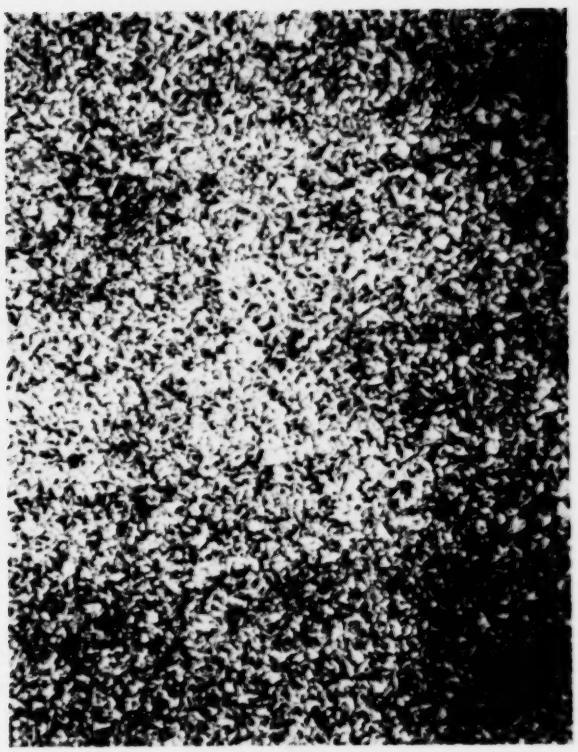


FIGURE 9

Microstructure of LC4 material (from 5" Casting)

Mag.X100.

establishing K_{IC}. The only exception in this case is that a higher loading rate was applied, and the peak load was used in calculating K_{ID}. Test temperatures were selected to suit a minimum value of impact energy value established by the CVN test.

4.7 Microstructure

Fig. 6 and 7 show the ferrite/pearlite microstructure of the normalized and tempered LCC material. In Fig 8 and 9, microstructure of LC4 materials from 2" and 5" castings are respectively shown. Since this material was subjected to quenching, much finer ferrite platelets, along with tempered bainite have resulted.

5. Test Results

5.1 Metallographic Examination

All test materials were subjected to metallographic examination. This procedure served as an effective means to determine the microctructural soundness of test

materials. In some cases, inappropriate heat treatment of test samples was identified and new test samples were substituted. Figures 6 - 9 show the microstructure of test materials derived from fracture toughness samples.

5.2 Chemical Analysis of Test Specimens

Each billet from which test specimens were extracted underwent spectrographic analysis. The chemistry of each material is shown on Table 1.

MATL	HEAT #	C	Si	Mn	Cr	Ni	Mo	Cu	P	S
LCC 2"	7031	.16	.52	1.18	-	-	-	.08	.010	.010
LCC 5"	7054	.14	.57	1.10	-	-	-	.04	.012	.011
LC4 2"	7072	.090	.59	.67	-	4.3	.05	.011	.010	.012
LC4 5"	7070	.10	.53	.71	-	4.15	-	.07	.012	.011

TABLE 1

5.3 Charpy Energy Evaluation

Table 2 lists the Charpy energy values of the test materials at various temperatures. The different test temperatures were selected with the intention of determining the ductile to brittle transition temperature ranges of the test materials.

Figures 10 - 13 are plots of the Charpy energy values recorded. The Charpy energy values of LCC materials are quite comparable to the published data (1) for the same materials. From the Charpy energy plots, a temperature range corresponding to the ductile-to-brittle transition range is deduced for each material.

MATERIAL	TEMP (°C)	CHARPY ENERGIES (CE) (ft. - lbf)	AVE. C.E.
LCC 2"	R.T.	64, 70. 60	64.66
	-20	15, 34, 35	28.00
	-40	10, 9	9.50
	-50	8, 11	9.50
	-60	14, 7	10.50
LCC 5"	R.T.	60, 67, 84	70.33
	-20	25, 14, 14	17.66
	-40	10, 7, 8	8.3
	-50	6, 7	6.5
	-60	5, 6, 5	5.3
LC4 2"	R.T.	70, 80, 80	76.60
	-20	50, 40, 44	44.66
	-60	20, 15, 15	16.66
	-80	7, 12.5, 6	8.50
	-102	6, 9, 12	9.00
LC4 5"	R.T.	75, 90, 86	83.60
	-20	60, 75, 58	64.30
	-40	60, 30, 60	50.00
	-80	30, 22	26.00

TABLE 2

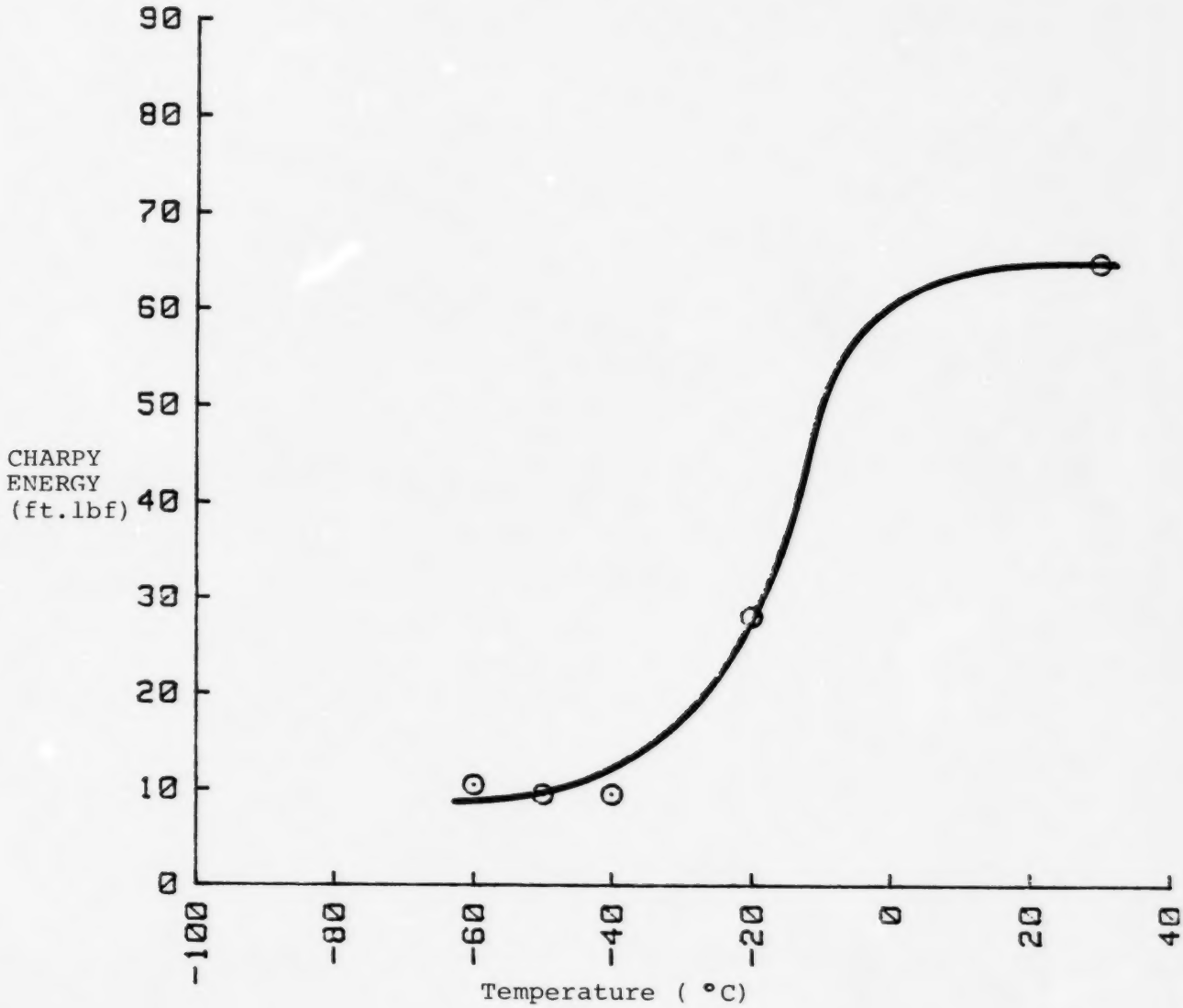


FIGURE 10: Charpy Energy vs Temperature Profile of LCC 2" Casting.

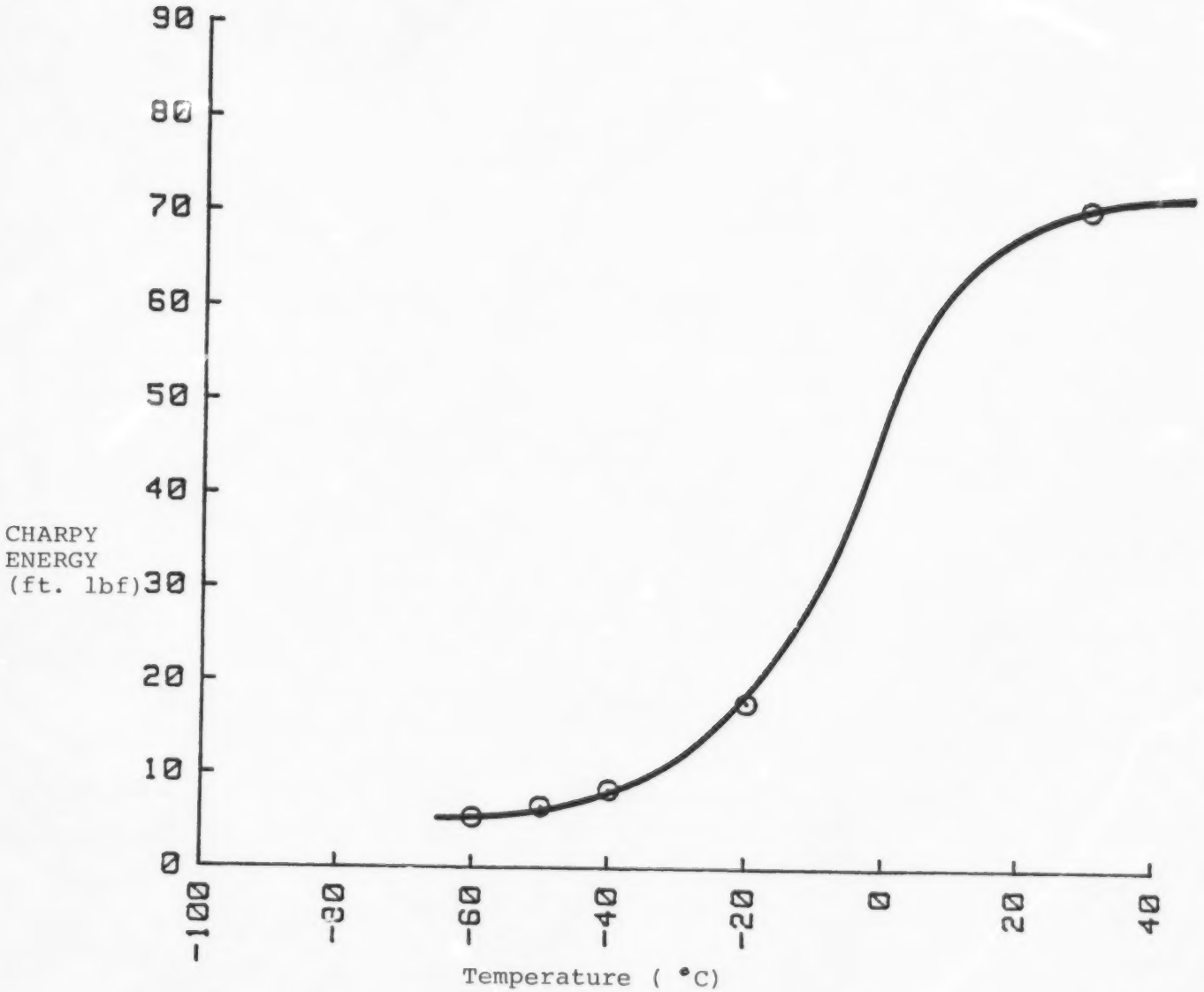


FIGURE 11: Charpy Energy vs Temperature Profile of LCC 5" Casting.

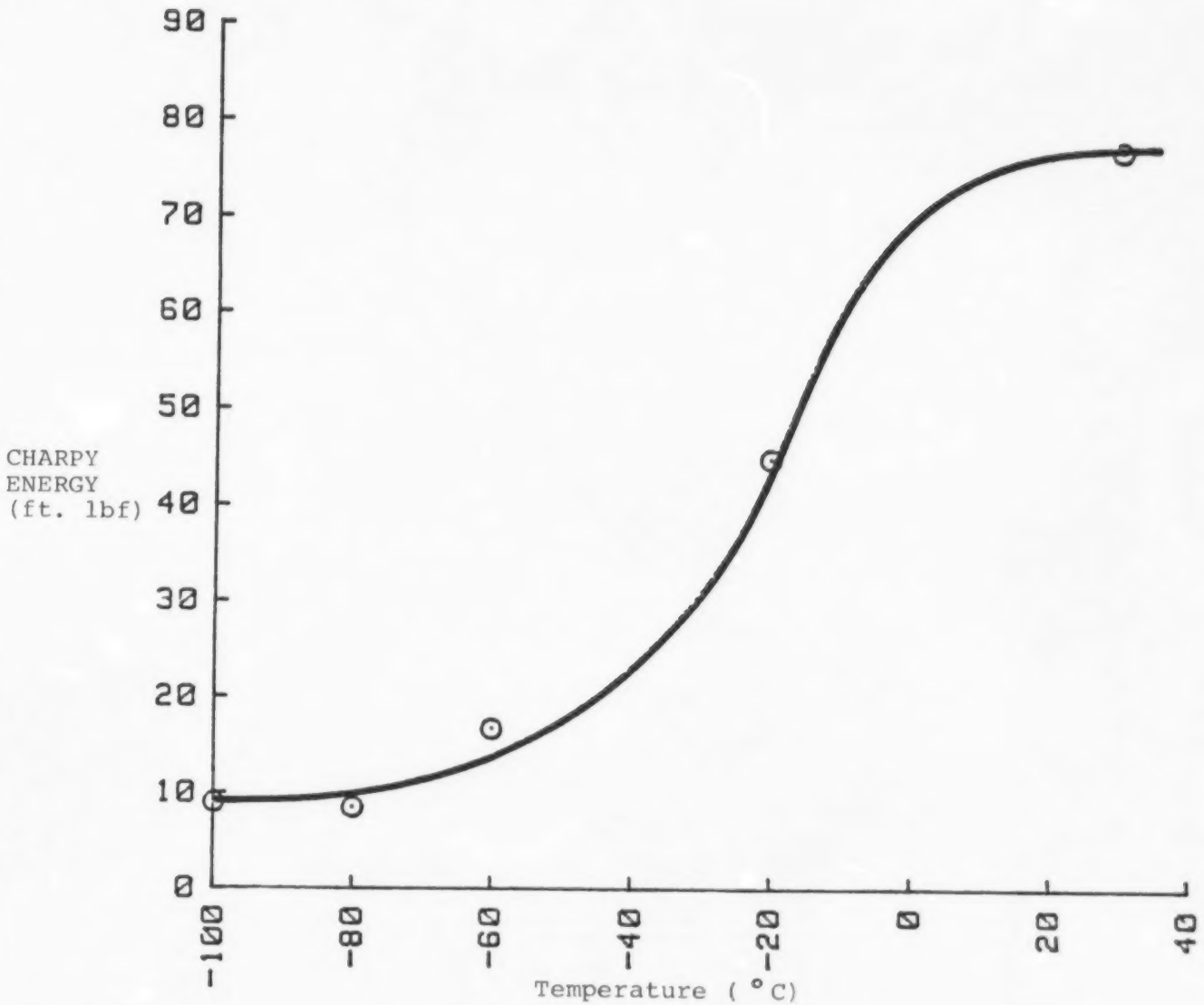


FIGURE 12: Charpy Energy vs Temperature Profile of LC4 2" Casting.

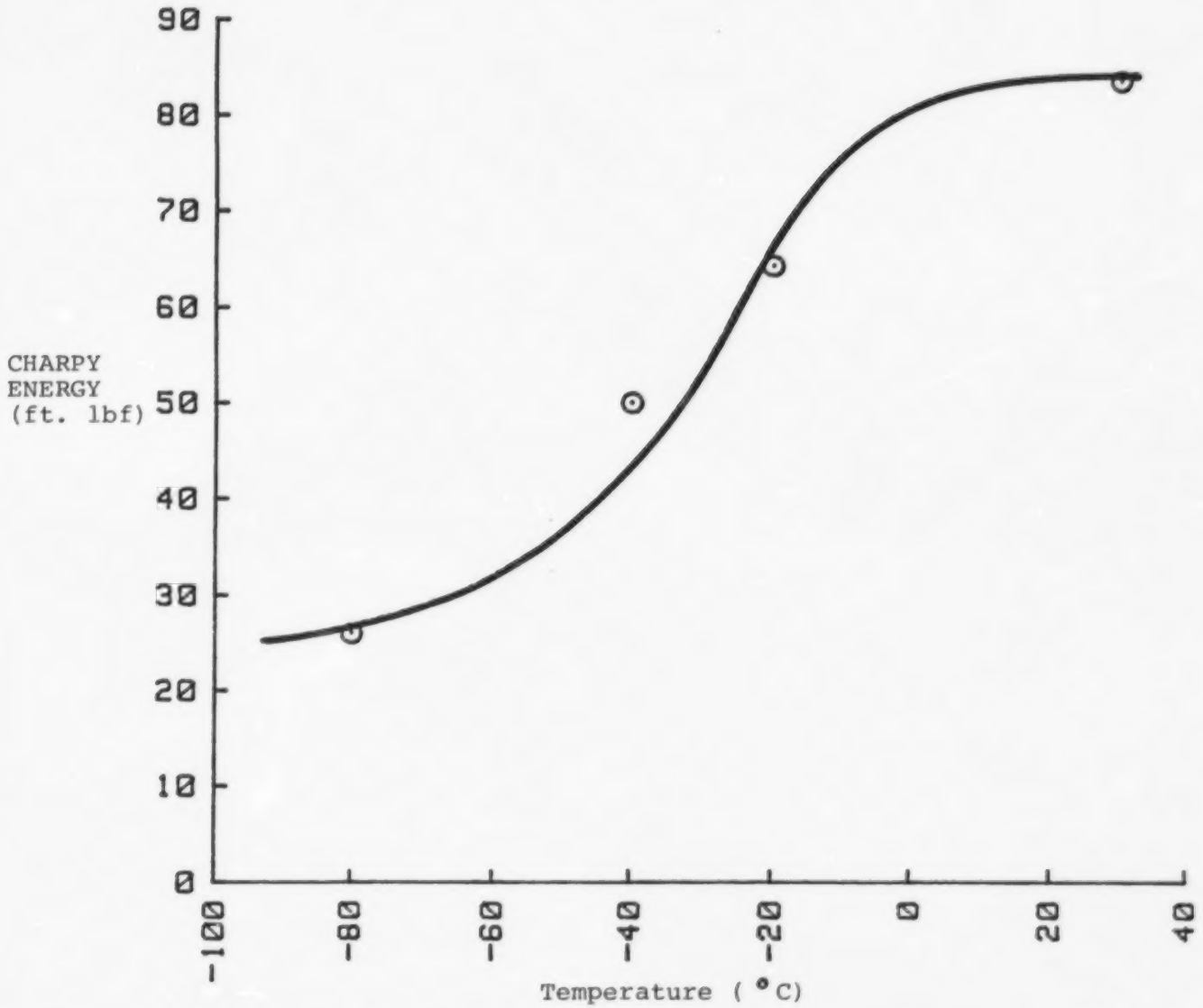


FIGURE 13: Charpy Energy vs Temperature Profile of LC4 5" Casting.

5.4 Tensile Testing

Table 3 lists the Tensile stress values of the test materials at various temperatures

TABLE 3

TENSILE STRESS VALUES OF LCC AND LC4 MATERIALS

MATERIAL	TEMP C	YEILD STRESS	MAX. STRESS
LCC 2" Casting	Room	34.3	68.6
	-20	-	73.2
	-50	-	76.2
LCC 5"	Room	47.6	77.1
	-20	-	79.6
	-50	-	82.5
LC4 2"	Room	-	84
	-20		90.3
	-50	-	96.5
	-78		99.4
LCC 5"	Room	68.7	83.2
	-20	-	88.3
	-50	-	94.6

5.5 Fracture Toughness K_{IC} and K_{ID} Testing

Table 4 lists the quasi-static, (K_{IC}) values of the four test materials at various test temperatures.

According to Table 4, the general onset of lower toughness values of each material occured at much lower temperatures than those deduced from the Charpy energy values. And in some cases, K_{IC} of a material was found to be temperature independent. However, because not all of the data met the K_{IC} test requirements recommended by the ASTM standard (Appendix I), the validity of the phenomenon observed above cannot be affirmed. Three parameters that are pertinent in qualifying K_{IC} requirements in this case are, sample geometry, test temperature and loading rate. Since the test temperature and loading rate are the pre-determined experimental conditions, sample geometry is important in this study. Basicaily, the size of the specimen determines whether the sample fails in either plane-strain or plane-stress condition. In ductile materials, a thicker sample is normally required to ensure that the plane-strain failure meets the ASTM requirements. In some of the tests reported below, it is apparent that the K_{IC} criterion can be met only with a thicker test sample.

TABLE 4

K_{IC} Values of LCC and LC4 Materials

Material	K_{IC} ($ksi\cdot\sqrt{in}$)	Test Temperature (degree C)
LCC 2" Casting	76.90* 77.43* 70.16* 44.62*	-30 -50 -72 -100
LCC 5" Casting	74.87* 73.03* 71.32*	-30 -50 -60
LC4 2" Casting	124.19* 144.51* 126.45 96.75 59.49	-10 -30 -50 -65 -80
LC4 5" Casting	98.24* 107.74* 101.80* 108.12* 106.69	-40 -60 -65 -80 -100

* K_{IC} test requirements (ASTM E399) not complied with.

In LC4 materials, the general trend of a lower ductile to brittle transition temperature zone indicated by K_{ID} testing was observed also. Instead of a transition temperature of around -20 deg. C as indicated by the Charpy energy values, a lower transition temperature of around - 50 deg. C, was evident in K_{ID} values.

Table 5 gives the dynamic fracture toughness (K_{ID}) values of the test materials at various temperatures. These data are also represented in Figures 14-17 for respective materials.

TABLE 5

K_{ID} Values of LCC and LC4 Materials

Material	K_{ID} (ksi $\sqrt{in}$)	Test Temperature (Degree C)
LCC 2" Casting	115.32	-40
	54.66	-50
	37.18	-60
	39.35	-72
	33.14	-100
LCC 5" Casting	98.84	-20
	48.88	-50
	50.63	-60
	36.80	-78
LC4 2" Casting	94.90	-40
	83.66	-65
	83.07	-80
	69.00	-100
LC4 5" Casting	113.38	-40
	76.84	-65
	69.46	-80
	68.71	-100

For LCC materials, a decrease in charpy energy values became siginificant when samples were tested at below -10 deg. C. In K_{ID} testing, a decrement is only evident at temperatures below -30 deg. C.

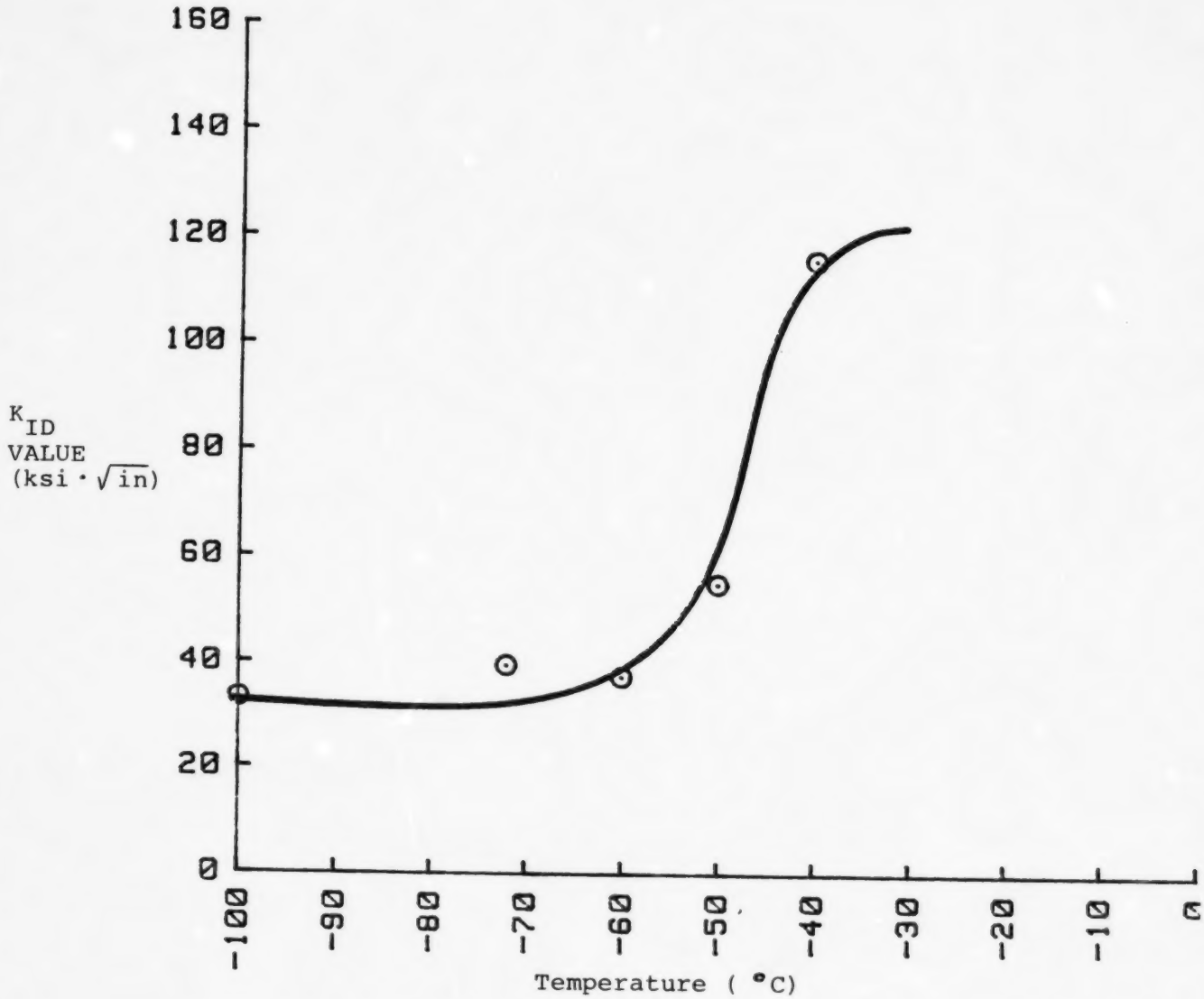


FIGURE 14: K_{ID} value vs temperature profile of LCC 2" Casting.

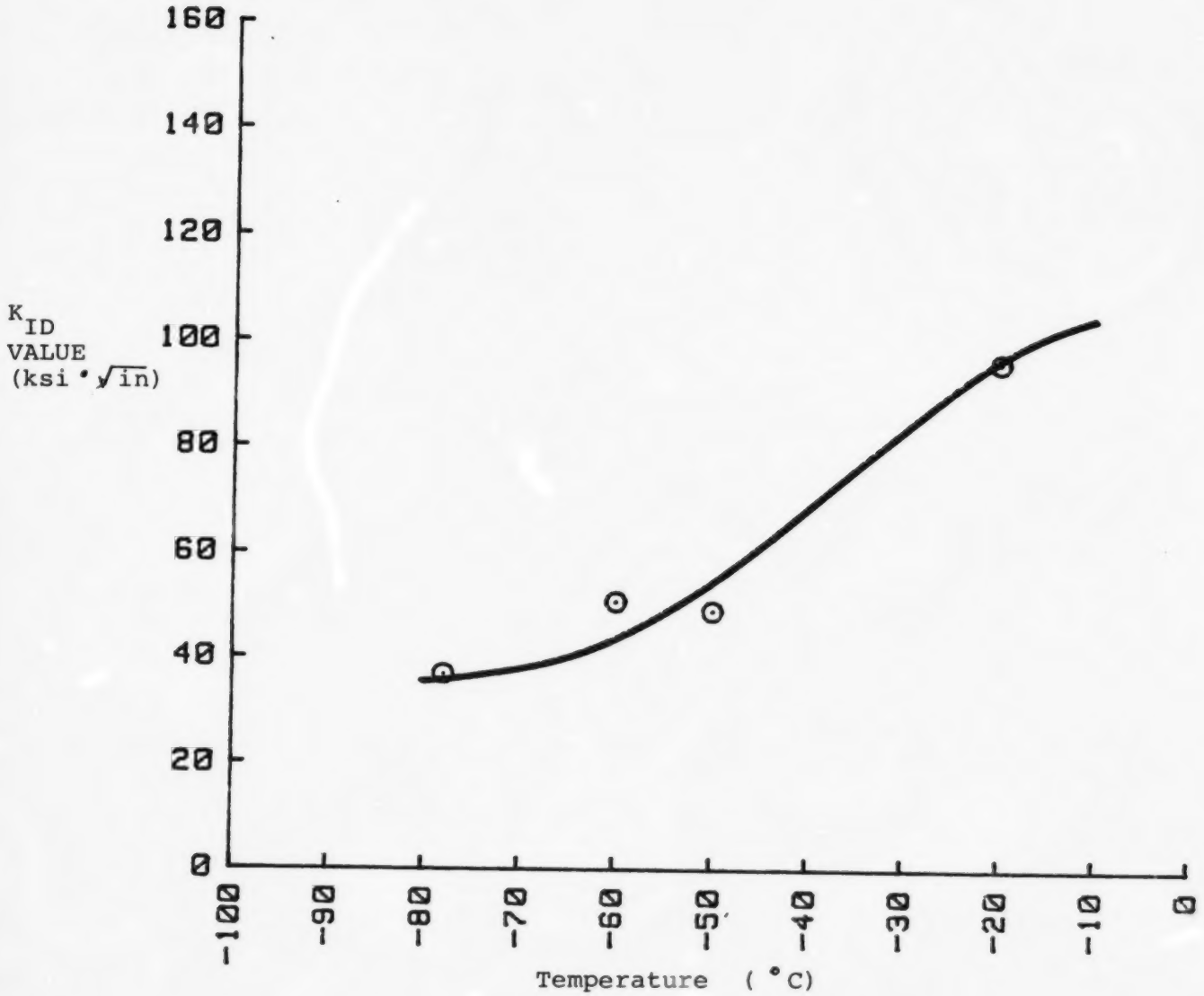


FIGURE 15: K_{ID} value vs temperature profile of LCC 5" Casting.

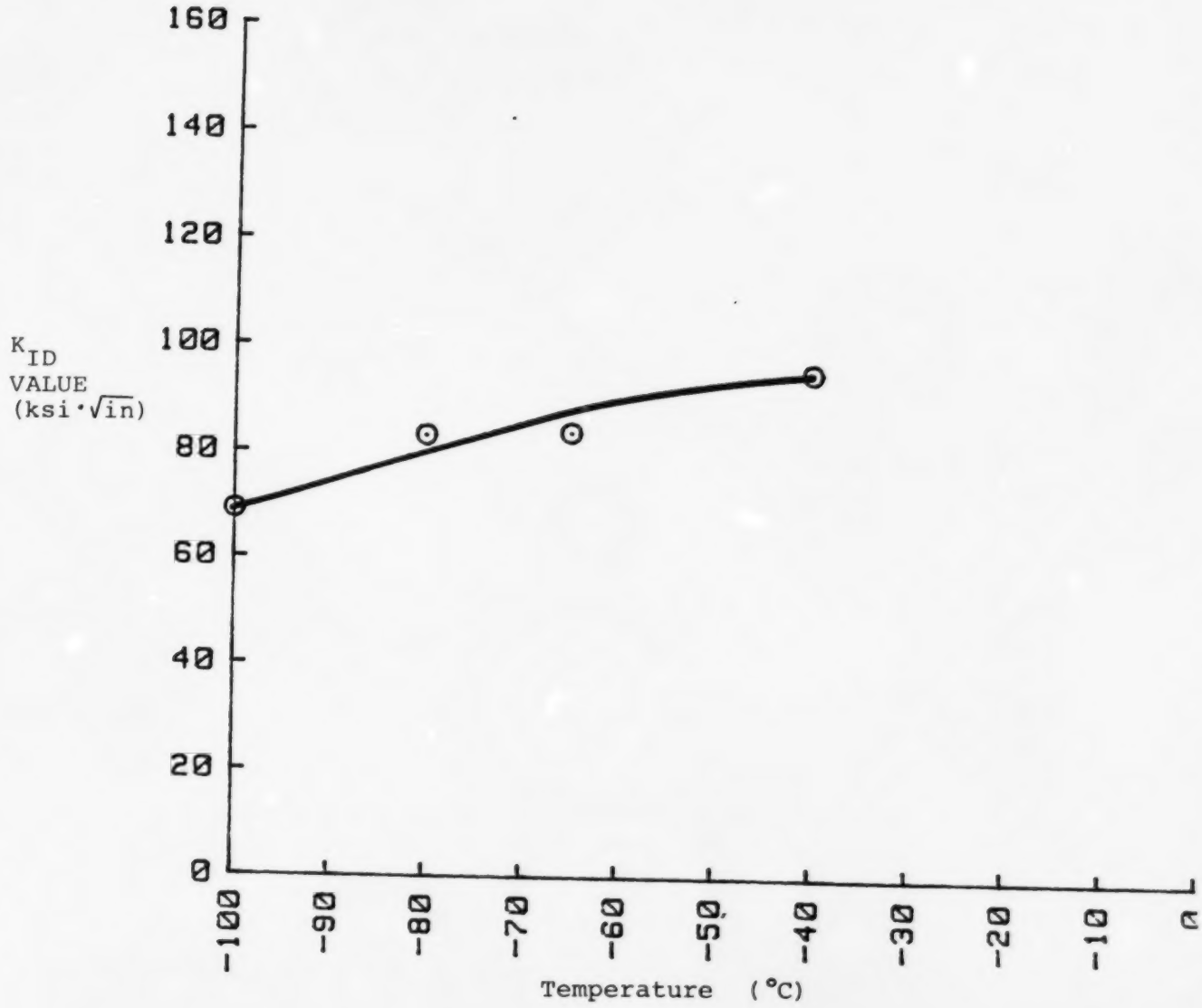


FIGURE 16: K_{ID} vs temperature profile of LC4 2" Casting.

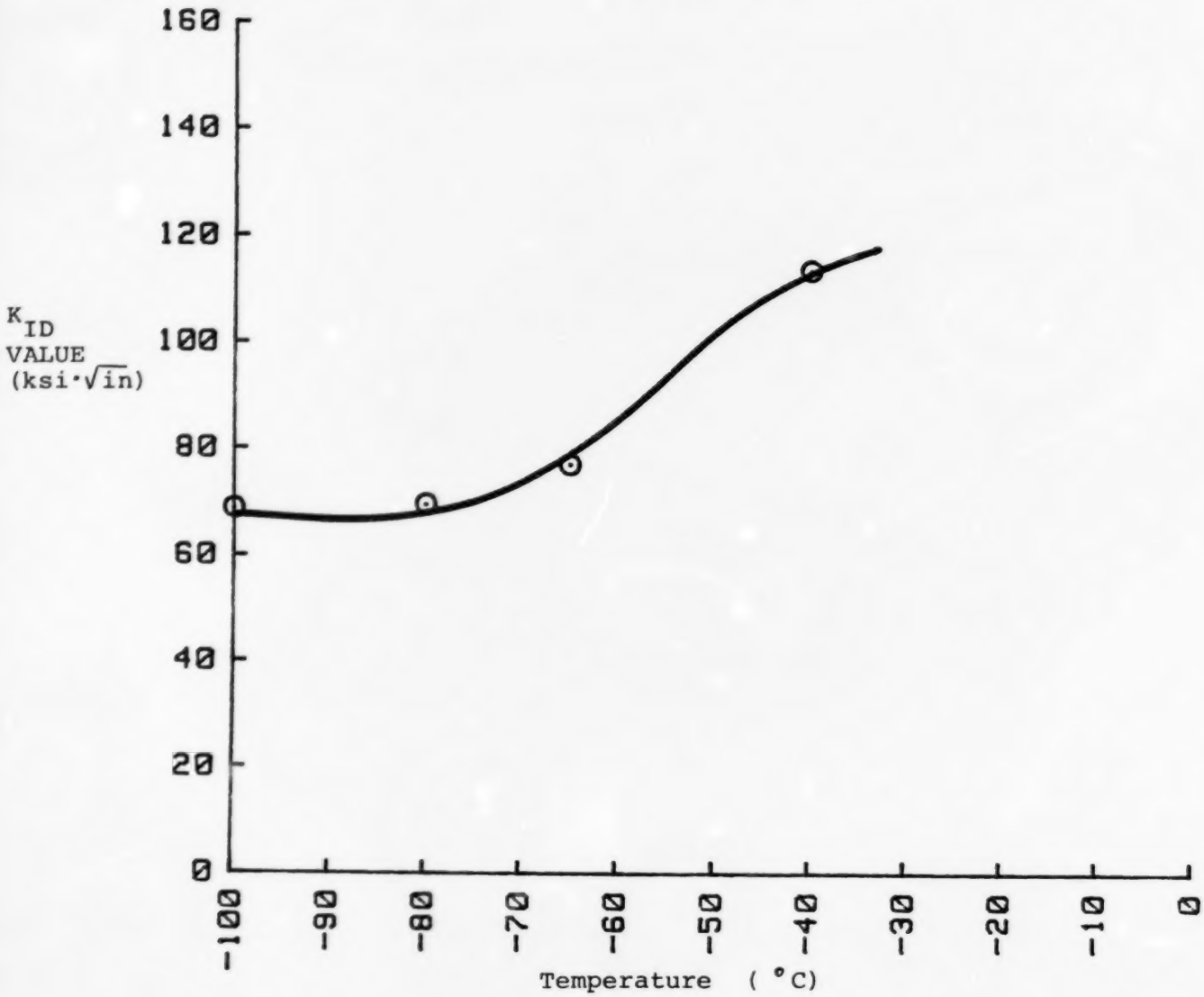


FIGURE 17: K_{ID} value vs temperature profile of LC4 5" Casting.

6.0 Calculation (See ASTM 399 Section 9 and Annex A3.5)

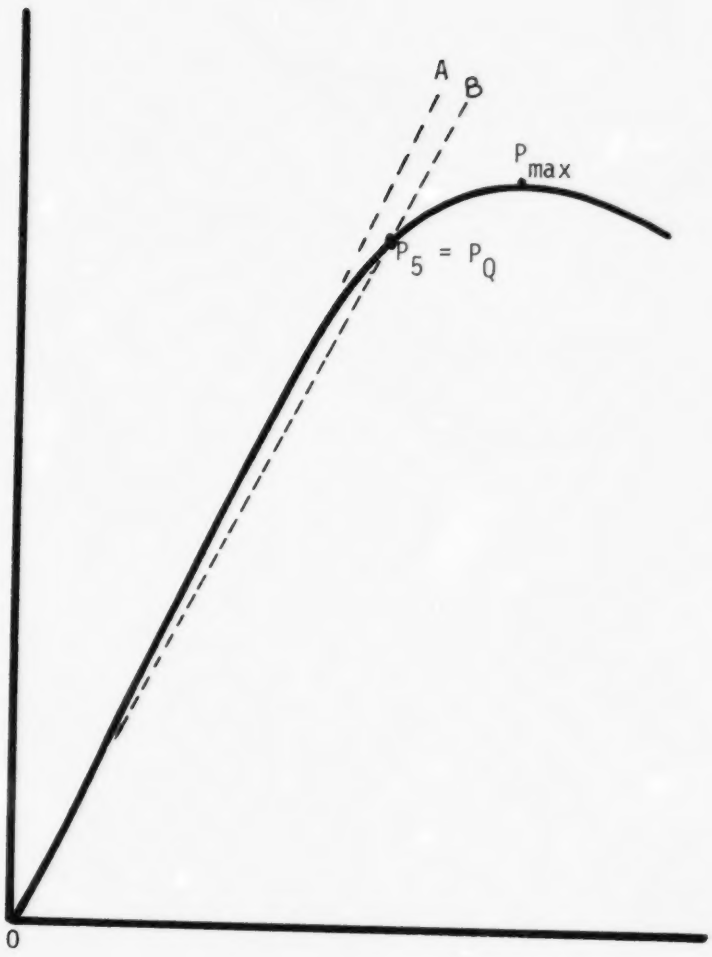
Figure 18 shows a typical load displacement curve obtained from the test sample. A line OB through the origin of the test record, with a slope of 0.95 of OA (where OA is the tangent to the linear part of the load-displacement curve) is drawn. Since all load-displacement profiles on the test samples were similar to those of fig. 18, the load PQ was defined as PQ = P5. (The point where line OB intersects the load displacement curve.)

The validity of the K_{IC} test can be deduced from the ratio $\frac{PMAX}{PQ}$, where Pmax is the maximum load the specimen was able to sustain (fig. 18). If the ratio does not exceed 1.10, a possible valid K_{IC} can be attained. On the other hand, if this ratio exceeds 1.10, then the test is not a valid K_{IC} test, for it is then possible that K_Q bears no relation to K_{IC}.

An alternate means of confirming the validity of K_{IC} is to calculate the value of $2.5\left(\frac{KQ}{\sigma ys}\right)^2$ where σ_{ys} is the 0.2% offset yield strength in tension. If this quantity is less than both the specimen thickness and the crack

length, then K_Q is equal to K_{IC}. Otherwise, the test is not a valid K_{IC} test.

If the test result fails to meet both of the above requirements, it will be necessary to use a larger specimen to determine K_{IC}. It should be noted here that there can be no advance assurance that a valid K_{IC} will be determined in a particular test. In many cases, the available stock of a material is just insufficient to provide a specimen of the required size. In such case, the specimen strength ratio determined by this method can have alternative significance. Unlike K_{IC}, this ratio is a quantitative number not a concept of linear elastic fracture mechanics. It can be a useful comparative measure of the toughness of materials, with the conditions that the specimens are of the same form and size, (though the size is insufficient to provide a valid K_{IC} determination) and of sufficient size that the maximum load results from a pronounced crack propagation rather than plastic instability.



TYPICAL LOAD - DISPLACEMENT RECORD

FIG. 18

For compact specimen calculate K_Q in units of Ksi. $\sqrt{in}$ (MPa.M^{2}) from the following expression (see ASTM 399-A 4.5)

$$K_Q = \frac{P_Q}{BW^{1/2}} x f\left(\frac{a}{w}\right)$$

where

$$f\left(\frac{a}{w}\right) = \frac{\left(2 + \frac{a}{w}\right)\left(0.886 + 4.64\,\frac{a}{w} - 13.32\left(\frac{a}{w}\right)^2 + 14.72\left(\frac{a}{w}\right)^3 - 5.6\left(\frac{a}{w}\right)^4\right)}{\left(1 - \frac{a}{w}\right)^{3/2}}$$

P_Q = load as determined in (fig. 18)

B = specimen thickness (fig. 4)

w = specimen width (fig. 4)

a = crack length (fig. 4)

7.0 Conclusion

The most widely used "Toughness" test in materials evaluation is the Charpy "V" notch (CVN) impact test. The toughness requirements for materials for specific situations are defined in terms of their CVN energy absorption value at a specific temperature. The basis for selecting materials with particular energy of absorption is commonly by service experience ---"if it worked before, it will work again". The fact is that in most structural applications, service failure is a rare occurance, and often is due to different causes, unrelated to material selection. Such experience does not really provide sufficient field data for a proper correlation between CVN energy absorption values and materials selection. In addition, CVN energy absorption values can not be mathematically related directly to structural design. It's use therefore is arbitrary at best.

A much more appropriate test technique for structural materials evaluation is by performing K_{IC} or K_{ID} tests. Since K_{ID} or plane-strain stress intensity factor are measured in terms of the allowable stress level for a given flaw size, it may be directly applied to the

selection of specific materials and component quality levels. It has been demonstrated that "fracture toughness" is dependant upon temperature, loading rate, and section thickness. Plastic flow properties also have an important influence on the resistance to crack extension under plane-strain conditions.

In this work, based on the limited test data, the K_{IC} values proved to be almost insensitive to temperature. This condition most likely results from the under estimated section thickness of the test samples. Since the plane-strain condition was not met even at low temperatures, much higher values of K_{IC} were observed. When a higher loading rate was used in the K_{ID} testings, the experimental conditions were closer to those of plane-strain condition; consequently temperature dependant K_{ID} values were obtained.

In conclusion, it would appear from the results obtained in this work, that since commonly used structural materials can be considered as ductile materials, and that through the use of rates of increase of stress intensity in excess of 150 Ksi$\sqrt{in}$/min acting upon

material test samples of convenient dimensions, K_{ID} toughness values are the most reliable tool in the selection of structural materials.

Reference:

1. K.G. Davis, J.G. Magney, G. Zairo, AFS Transactions, 83-58, pg. 325.

2. A.A. Griffith - Phil Trans - Royal Society, Vol. 221-1920 Page 163.

Appendix "A"

1.1 A questionaire (see exhibit "A") was sent to all the active steel foundries in Canada. Due in large part to the very competative nature of the current business cycle only a small sampling of replies were received. However that small sampling was enough to indicate that there is no real agreement among foundries regarding the heat treatment of steels. No significant differences were reported, however, no two treatments were the same.

- normallizing temperatures ranged from 1600 F to 1850 F
- normallizing soak times ranged from 1/2 hour per inch of section thickness to a flat 7 hours minimum regardless of thickness.
- tempering temperatures ranged from 1100 F to 1400 F

The castings used in this study were produced to our "normal" production procedures. The heat treatment chart is given on page - of the main report. The LC4 material were quenched in a large tank of ice water. A skid mounted tank of approximately 300 gallons was

filled with tap water and left outside over night. The next day in preparation for the quenching operation, the tank was brought into the heat treat area. The layer of ice (approximately 2" thick) which had formed during the night was broken up and the castings were raked out of the furnace into the water bath. The water was agitated manually until the evolution of steam bubbles had subsided. At this point although some chunks of ice were still evident floating on the surface of the water, the water was "luke warm" to the touch.

It should be pointed out that since this work was processed in March the quench water was iced. Had the time of year been July the water quench would have taken place using tap water at normal tap water temperature.

The fore going is perfectly consistent with our normal commercial production.

EXHIBIT "A"

FOUNDRY QUESTIONNAIRE

CANMET PROJECT NUMBER 370002

TITLE: TO DETERMINE THE DYNAMIC TOUGHNESS PROPERTIES OF CAST STEELS

WORK ON THIS PROJECT IS BEING CONDUCTED BY:
ALLOY CASTING INDUSTRIES LIMITED
and
ONTARIO RESEARCH FOUNDATION

Under the auspices of the Canada Centre for Mineral and Energy Technology; Energy, Mines and Resources, Canada

Your reply is requested before 31 January, 1984

1. If you received an order for a Carbon Steel Casting, which you suspected would be used in a low temperature application, what would be your response?

.....

.....

.....

2. What metal would you supply?

CHEMICAL COMPOSITION

ASTM DESIGN	C	Si	Mg	P	S	Ni	Cr	Mo	Reason for Selection

3. What size range could you offer?

	MAXIMUM	MINIMUM
CASTING WEIGHT		
SECTION THICKNESS		

4. What is your melting method?

FURNACE TYPE: INDUCTION ..... ARC ..... OTHER .....

BATH SIZE: SMALLEST ..... LARGEST .....

POURING TEMP's.: LOWEST .....°F HIGHEST ..... °F

5. What is your method of obtaining Chemical Analysis? .....

.....

How many elements? .....

6. What heat treatment would you routinely supply?

NORMALIZE	YES	NO	TEMPERATURE		SOAK TIME
QUENCH	YES	NO	TEMP.	SOAK TIME	QUENCH MEDIA
TEMPER	YES	NO	TEMPERATURE		SOAK TIME

7. Casting Upgrading Techniques:

a) Defect Identification Method: (Please check)

X-RAY .....

ULTRA-SONIC ..... MAG. PART ..... DYE PEN.....

b) Welding Procedures:

AC ..... DC .....

ROD DESIGNATION .....

c) Shot Blast Media: .....

8. What QC Inspections do you routinely make?

a) PHYSICAL TESTS

	IN HOUSE	OUTSIDE LAB
Tensile strength		
Yield strength		
Elongation		
Impact		
Hardness		

b) QUALITY CHECKS PRIOR TO SHIPMENT

	IN HOUSE	OUTSIDE LAB
Mag Particle		
Radiographic		
Liquid Penetrant		
Ultra-sonic		

If additional information and/or clarification is required, to whom should the questions be directed?

Name: .....

Title: .....

Should you require clarification of the questions or additional information, please call or write:

Alloy Casting Industries Ltd.
P.O. Box 580,
New Hamburg, Ontario
N0B 2G0

Mr. Brian J. Gilson, P.Eng.